

Large-scale plasma experiments, their analysis and numerical modeling

A.S. Kholodov¹, E.L. Stupitsky²

¹ *Moscow Institute of Physics and Technology, Russia*

² *Central Institute of Physics and Technology, Sergiev Posad, Russia*

Over last few decades plenty of various plasma rocket experiments in the upper ionosphere have been carried out. First of all, these are experiments with emission of about 1÷30 kg of semi-ionized substances such as barium (*Ba*) into the ionosphere. In particular, in these experiments, an interesting phenomenon was revealed. It is the phenomenon of barium stratification in a direction perpendicular to the geomagnetic field. In the last years, due to the efforts of Russian and American scientists, two rocket experiments were carried out. A plasma jet of about 30 gr was emitted into the ionosphere from a special generator. In these experiments scientists found out an effect of abnormally fast diffusion of a magnetic field into plasma, and it was the first time the effect had been observed so distinctly in such a large-scale process. The most powerful are the experiments of a similar geophysical type, which use explosions of "Argus" and "Starfish" kind. In these experiments $\sim 10^6$ gr of highly ionized plasma with the energy of $10^{19}\div 10^{22}$ erg was thrown out into the ionosphere. The value of this experimental material is not only in the initial parameters originality, but also in the complex character of the influence on the ionosphere, in particular, by rigid radiation and a powerful stream of electrons with the energy of several MeV.

It's absolutely clear, that scientific and applied value of similar experiments depends, first of all, on how deep we will manage to understand and numerically model their results. The complexity of the problem is caused, first of all, by three-dimensional character of plasma current and the necessity of taking into account a big number of physical processes in plasma, influencing its dynamics.

Long-term experience in searching numerical solutions of plasma problems allowed us to develop an algorithmic base, which is universal enough for interpretation and forecast of large-scale plasma experiments of different kinds. In this work we gave an overview on this methods and results, which we archived using them. These results allowed us to attain better understanding and forecasting of the effects, which are the most important from scientific and practical points of view ones.

In the experiments with emission of heated barium cloud, character of cloud's motion is determined by ionization kinetics. The main source of information about plasma state in experiments is spectral structure of radiation. This makes us to calculate nonequilibrium ionization and temperature of electrons in the single unit with level-by-level kinetics of electrons. Thus, we created quite a universal algorithm, based on splitting of physical processes. This algorithm allows calculating main ionization parameters of plasma -

$T_e \leftrightarrow n_e \leftrightarrow n_k$, where T_e, n_e, n_k - temperature of electrons, concentration and population of excited states of particles. On the Fig. 1,2 you can see dependence on time of the temperature of the electrons and coefficients of radiation of lines in the expanding barium cloud with initial parameters: $T=3500$ K, $\rho = 5.5 \cdot 10^{-4}$ g/cm³. Calculations shown that we can find very strong nonequilibrium in distributions of T_e and n_e in all experiments with barium, what leads to nonequilibrium in linear radiation. That's why the only way to determine behavior of the parameters is to use algorithm similar to described above [1].

The detailed description of ionization kinetics, especially photoionization and magnetic field, allowed creating new method describing stratification of extending barium cloud [2], which was later confirmed by precise calculations [3]. This method allows the main features of stratification, in particular equivalence of distances between condensation layers. On the Fig 3,4 you can see experimental [4] and calculated [3] results on stratification. Difference in time does not play a basic role, because when the time passes, only the scales of the picture varies, but its details do not – they are formed on the early stages of motion. Calculations of heterogeneities in magnetic field connected with stratification, jet streams and so on, demand much to difference schemes and to calculation of diffusion coefficient of field into plasma, which is determined by temperature of electrons and concentration. But during plasma motion in magnetic field, micro-instabilities can be formed, what can strongly increase the coefficient of diffusion. There where several Russian-American rocket experiments with emission of plasma jets in the upper ionosphere during several last years. One of the main results of these experiments was the fact of abnormally fast diffusion of magnetic field into plasma. This result is described by progress of double-stream instability on the external layer of plasma, which interacts with the magnetic field, as it was shown by computer modeling. From the Fig.5 you can see that taking this effect into account leads to coordination between experiment and calculations [5].

The most interesting large-scale geophysical experiments are nuclear explosions in the upper ionosphere. Big initial energy, large scales of perturbations and saturation with physical processes, makes it a hard task to create a mathematical model of this class of physical processes. That's why in the world's literature there is no works on computational modeling of the nuclear explosion in ionosphere or magnetosphere. For last several years we managed to archive new results in solution of this problem, which has not only scientific, but also a big practical value [6]. We shown that MHD-approximation is applicable in this case, and developed three-dimensional algorithm with high order of approximation taking into account main physical processes – ionization kinetics and field diffusion. Algorithm has a complex structure and allows calculating all the dynamics of the plasma from 10^{-6} to 100-200 seconds, when perturbation already has global scale. On the Fig. 6 you can see an example of calculation of nuclear explosion with energy $\sim 10^{22}$ erg, which was made on the height of 150 km after 5.9 seconds of motion. It's important to notice two results: first of all,

after 2-3 seconds of motion it becomes a really three-dimensional one, and also all the affected area is separated into two zones – nearest one, where we can see a strong heating and where all the plasma and heated up by the shock wave air is situated, and the far one, where the relatively weak MHD-wave is spreading, where changes in temperature and density are relatively weak. We assumed in our calculations that air in upper ionosphere is ionized by roentgen radiation of the explosion. Thus MHD-perturbation appears while plasma is braking, when it's distribution is near to spherical, and it moves with alfvén speed of $V_A = B / \sqrt{4\pi\rho_i}$ reaching far distances very fast, saving it's spherical structure. Further development of the algorithm is connected mainly with expansion of it's range of applicability.

Plasma of the explosion also emits a powerful stream of electrons with energy about several MeV, which, while moving along the geomagnetic field into lower ionosphere and ionizing it, arrange a system of currents. Using the method of big particles, we developed an algorithm modeling the dynamics of this system, taking into account self-coordinated electric field between big charged particles. This method allowed us to calculate distribution of charge between the source and the ionosphere and reach the semi-stable mode. It was found that on the heights of about 30-60 km there appears a negative charge of about 26-32 K1 [7].

Thus complex of algorithms, which allows to explaining and forecasting of a wide spectrum of large scale geophysical experiments, is developed.

Literature

1. S.N. Prijatkin, E.L. Stupitsky. Space researches, t. 30, v.2, 1992, p.253.
2. E.L. Stupitsky, S.I. Kozlov. Space researches, t. 28, v.4, 1990, p.555.
3. E.L. Stupitsky, A.V. Shapranov. Space researches, t. 36, v.5, 1998, p.475.
4. Hacrendel G. Space research XIII Academic – Velag. Berlin, 1973, p. 601-603.
5. E.L. Stupitsky, A.Yu. Repin, A.V. Shapranov, IV International Conference Plasma Physics. Minsk, 2003, v.1, p. 249.
6. E.L. Stupitsky, A.S. Kholodov, A.Yu. Repin, Ja.A. Kholodov, IV International Conference Plasma Physics. Minsk, 2003, v.1, p. 253.
7. V.V. Kurnosov, E.L. Stupitsky. Geomagnetism and aeronomics. t.43, №3, 2003.

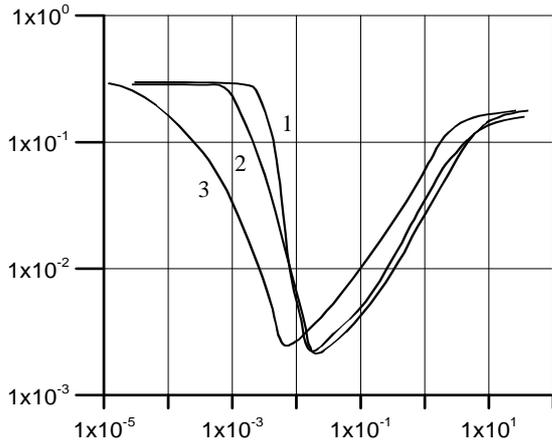


Fig. 1 Alteration in time of temperature of the electrons
1-center; 2- middle area; 3 –edges

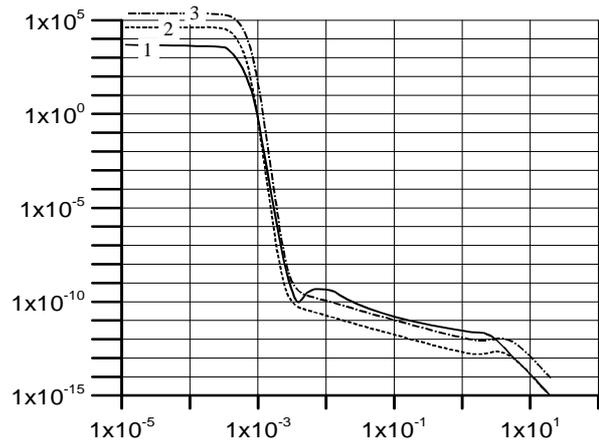


Fig. 2 Coefficients of emission of main spectrum line in the center of the clot
1- $\lambda=7911 \text{ \AA}$; 2- 5535Å; 3 – 15000Å

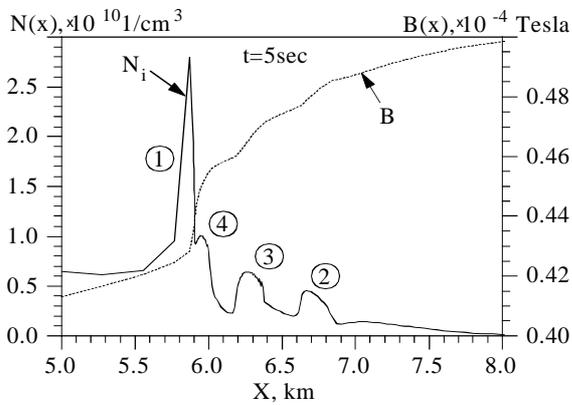


Fig. 3 Appearance of the fourth stratum страты

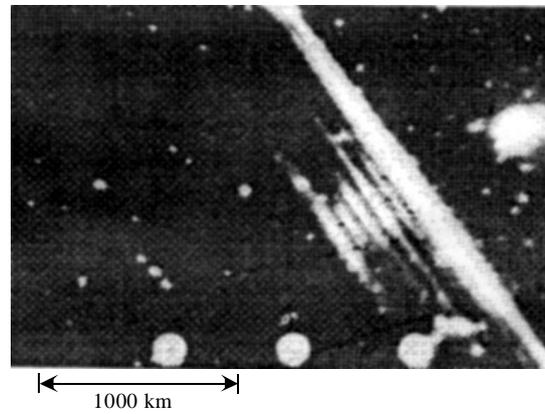


Fig. 4 Photometrical experiment

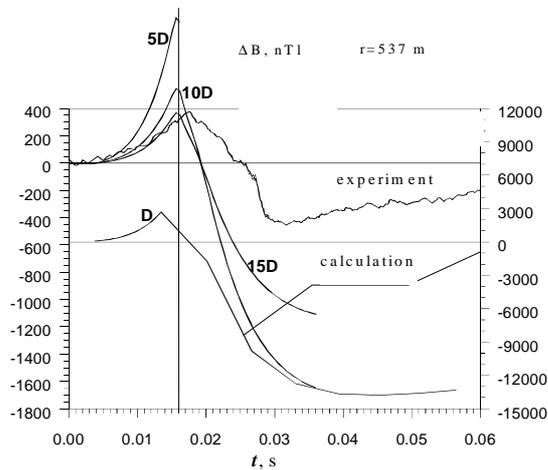


Fig. 5 Distribution of the field on the front of plasma jet.
D – classical diffusion.

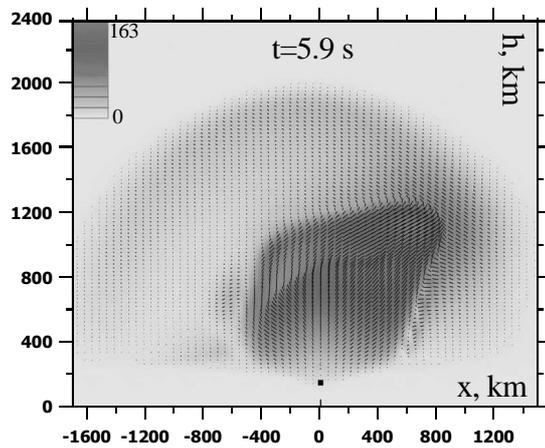


Fig. 6 Field of the speeds after the explosion on the height of 150 km after 5.9 seconds of motion in meridian plane.